A VIBRATION TEST OF EARTHQUAKE INDUCED HYDRAULIC EFFECTS OF LIQUID-FILLED PIPELINES

N. Ogawa(I)

SUMMARY

Liquid-filled pipelines are expected to undergo transient hydraulic :ects as a pressure rise during earthquakes. In this study, an experiıt on the dynamic response of a real scale piping system was carried out ing a large scale shaking table. The tested system was a 40m long raight pipe of 318mm diameter with both dead ends and ten supports. It s pressurized up to the stationary value 490kPa(5kg/cm^2). The system owed the very sharp resonance, and this characteristics was analyzed ing a simple coupled model. The experiment and analysis suggested that coupling of liquid and piping system would be one of the important ctors for seismic response estimations of liquid-filled pipelines, espeally, closed and relatively low pressure systems.

INTRODUCTION

Liquid in a pipeline is usually considered only as a distributed added .ss to a piping system in the seismic response estimation of pipeline 'stems. This estimation, which is called "a rigid water model" in this per, may not be exact for a long pipeline excited in axial direction cause of the spring effect of liquid due to pressure wave propagation ıd usually very small friction of pipe and liquid.

Liquid effects in seismic response have not been so much recognized ı the aseismic design of pipelines. This is because the damages of pipeines were mainly caused by forced ground motion or soil-pipe interaction. ıt, as Young and Hunter described in their research paper(Ref. 1), liquid ffects may be important as one of the "potential damage factors" in seisic response of relatively low pressure and large diameter pipelines.

In the previous studies on this subject(Ref. 2-4), pipings without upport system were used to estimate the pressure rise when deformed or oved forcedly in the same manner as by ground motion. But, in the real ases, a support system has important effects such as on resonance freuency and damping. Then the coupled response analysis of pipe-liquidupport systems would be required to estimate liquid effects. This paper resents experimental results and a simple analysis of such a system.

AN OUTLINE OF EXPERIMENT

A 40m long straight steel pipe(SGP300A of JIS, outer diameter 318.5mm, :hickness 6.9mm) was used for the vibration test (Fig.1). The expected :esonance frequency of 40m liquid column itself was about 12.5Hz in the

---

(I) Research Engineer, National Research Center for Disaster Prevention, Tsukuba Science City, Japan

case of 1000m/s pressure wave velocity. The large scale shaking table (15m x 15m) of the National Research Center for Disaster Prevention, which has 6cm p-p displacement amplitude and 360tons shaking force, was used for axial vibration of the test pipeline.

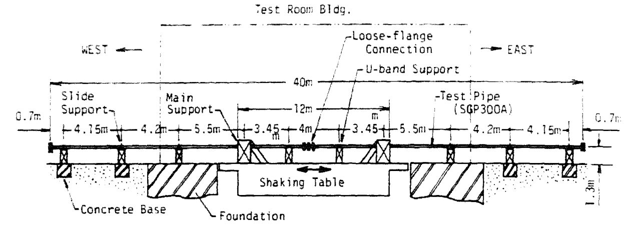


Fig.1 An outline of experiment

The test pipe was made by welding of standard pipes except for the central loose-flange connection. The pipe was supported by ten support structures; two were for connection of axial shaking force and others for dead load support and restriction of large lateral vibration. Two main supports, which were relatively rigid and connected to the test pipe by welding. Two auxiliary U-band supports were set up on the shaking table.

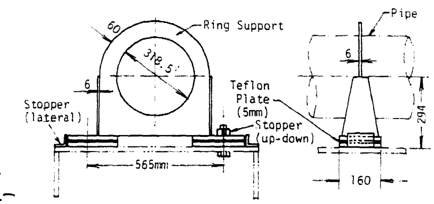


Fig.2 Sliding support

The 25m long part of the test pipe was extended outside the shaking table, and this extended part was supported by six sliding supports (Fig.2) which did not restrict axial movements of the test pipe. Both ends of the pipe was closed by 26mm thickness flange plates. For removing air in the test pipe before shaking tests, four air valves were set up at the upper part of the pipe.

Shaking tests were carried out in the empty and water-filled conditions. In latter case, water was pressurized up to the stationary value 490kPa ($5kg/cm^2$) after removing air in the pipe. The measurement points for water pressure and pipe acceleration are shown in Fig.3,4. The data were recorded by digital and analogue data recorders, and in this paper, the data analysis was carried out only on the water pressure fluctuations from the stationary value 490kPa ($5kg/cm^2$) and the axial pipe accelerations. The pipe response will greatly depend on the amount of the air in the pipe, so some pressurized shaking tests were repeated in a similar way.

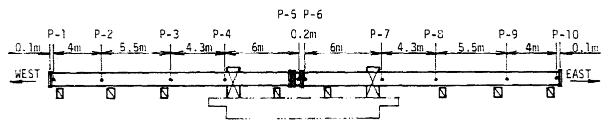


Fig.3 Measurement points of pressure

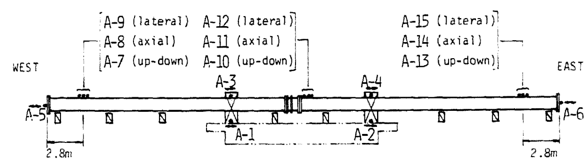


Fig.4 Measurement points of acceleration

ANALYTICAL MODEL

Fig.5 shows a simple model of the test pipeline for axial direction response analysis. In this model, a pipeline is treated as a rigid container in which longitudinal deformations of pipe are neglected and the support system is simplified as a spring-dash pot system of one degree of freedom. Liquid behaviour is treated as a one dimensional pressure wave. Non-linear behaviours such as a column separation are omitted in this analysis, and further, pipe-liquid friction is linearized for steady state response analysis.

The equations for analysis are given by:

$$M\ddot{y} + C\dot{y} + Ky = -M\ddot{\xi} + A[p(L) - p(0)] + F \quad \cdots\cdots\cdots\cdots(1)$$

$$\frac{\partial u}{\partial t} = -\frac{1}{\rho}\frac{\partial p}{\partial x} - Qv \quad \cdots\cdots\cdots(2)$$

$$\frac{\partial p}{\partial t} = -\rho a^2 \frac{\partial u}{\partial x} \quad \cdots\cdots\cdots(3)$$

$$u = v + \dot{y} + \dot{\xi} \quad \cdots\cdots(4)$$

$$F = \int_0^L \pi D \tau_0 \, dx = \int_0^L \rho A Q v \, dx \quad \cdots(5)$$

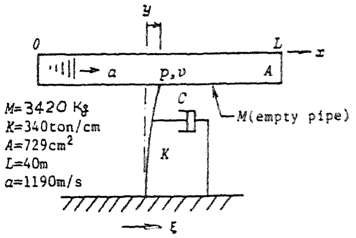


Fig.5 Analytical model

Where:

M: effective mass of empty piping system

C: coefficient of damping force of support

K: spring constant of support

$\omega_0 = 2\pi f_0 = \sqrt{\frac{K}{M}}$: natural frequency of empty system

$h = \frac{C}{2\omega_0 M}$: damping factor of empty system

L: length of pipe

D: pipe inner diameter

ρ: density of liquid

a: pressure wave velocity of liquid

Q: linearized pipe-liquid friction factor

t: time

x: axial coordinate along a pipe

y: relative displacement of rigid pipe to base

ξ: base displacement (excitation)

p: pressure fluctuation of liquid

u: liquid absolute velocity

v: liquid velocity relative to pipe

A: pipe inside area

τ_0: pipe-liquid friction force per unit area

F: total friction force along a pipe wall

For steady state analysis, we use the solutions as follow:

$$\xi = Re^{j\omega t},\ y = Ye^{j\omega t},\ v = V(x)e^{j\omega t},\ p = P(x)e^{j\omega t} \quad (j=\sqrt{-1}) \quad \ldots\ldots\ldots\ldots (6)$$

The total friction force which acts on a rigid pipe from liquid along a pipe wall is estimated by equations (2),(5) and (6) as the following:

$$F = \frac{\rho A Q}{j\omega + Q}\left\{-\frac{1}{\rho}\left[P(L)-P(0)\right] + \omega^2 L\,(R+Y)\right\}e^{j\omega t} \quad \ldots\ldots\ldots\ldots\ldots (7)$$

From equations (1)-(7) and the boundary conditions v=0 at x=0,L, we can obtain the steady state response of pressure at x=0 and pipe axial acceleration as the following:

$$\frac{Y+R}{R} = \frac{\omega_0^2 + j(2h\omega_0\omega)}{\omega_0^2 - (1+m)\omega^2 + j(2h\omega_0\omega) + \dfrac{m\omega^4}{a^2 s^2}\left\{\dfrac{\tanh(sL/2)}{(sL/2)} - 1\right\}} \quad \ldots\ldots\ldots (8)$$

$$\frac{P(0)}{(j\omega)^2 R} = \frac{R+Y}{R}\cdot\frac{\rho L}{2}\,\frac{\tanh(sL/2)}{(sL/2)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

where:

$$m = \frac{\text{Mass (water)}}{\text{Mass(pipe)}} = \frac{\rho A L}{M} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

$$s = \alpha + j\beta,\ \left.\begin{matrix}\alpha\\ \beta\end{matrix}\right\} = \sqrt{\frac{\omega\sqrt{\omega^2+Q^2} \mp \omega^2}{2a^2}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (11)$$

The above solutions show the response of an empty pipe support system if m=0, and show the response of a rigid water model if $a \to \infty$ $(s \to 0)$. The mass ratio m was about 0.853 for the tested pipeline.

RESULTS AND DISCUSSIONS

Vibration Characteristics of An Empty System

Fig.6 shows the measured and computed natural frequencies and vibration modes of the tested system in axial direction. The computed values were obtained by use of beam elements, and the measured values by man power shock test. Only the first mode can be predominant in the shaking table test, then f_0 of the analytical model is given as 47Hz. The damping factor of the empty system was obtained as about h=2.5% from the spectrum analysis. This value may be lower for analysis of shaking table test because it was obtained by considerably low level excitation.

Fig.6 also shows the computed

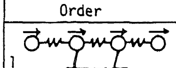
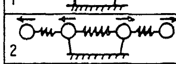
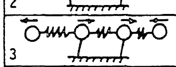
Order	empty	water-filled
1 	51Hz (47Hz)	36Hz*
2 	66Hz (62Hz)	46Hz*
3 	114Hz	85Hz*

Fig.6 Natural vibrations
()=measured, *=rigid water model

values of the liquid-filled system which were obtained by treating liquid as distributed added masses to the pipe. Measured values for such a rigid water model can not be obtained because of liquid-pipe coupled vibration.

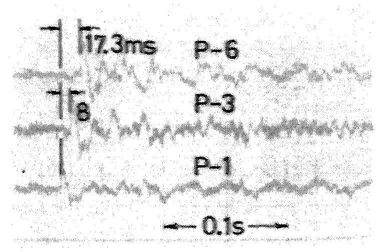


Fig.7 Pressure wave propagation in the pipe

Pressure Wave Propagation in Water

The measurement was done by longitudinal shock at the end of pressurized pipe after removing the air. Fig.7 shows the recorded waves from which the velocity was estimated as about 1150-1200m/s. The wave velocity has much effect on the resonance characteristics of the system, then the measurement was done before and after shaking table tests and about the same values were obtained. We use the value of 1190m/s for analysis considering the above result and the resonance test results.

Results of The Resonance Test

The resonance test was done by use of sinusoidal sweep excitation of lower level to avoid negative pressure response. Fig.8 shows the pressure response at a pipe end. The response values are shown as the amplitude ratio to the shaking table acceleration. The very sharp resonance is seen at about 14.3Hz and the maximum response value shows the possibility of negative pressure at resonance in low pressure systems even if excited at

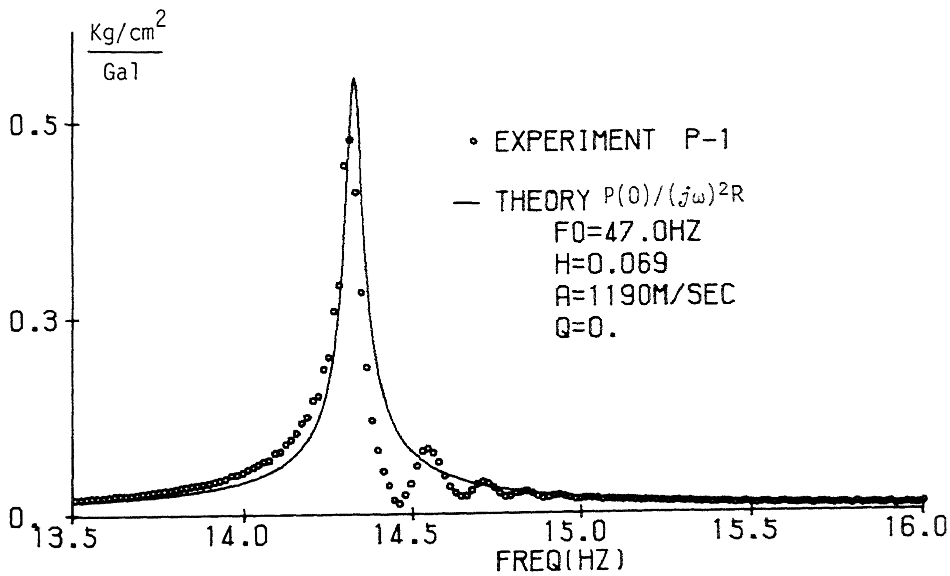


Fig.8 Pressure response P-1/A-2 by experiment and comparison with theory

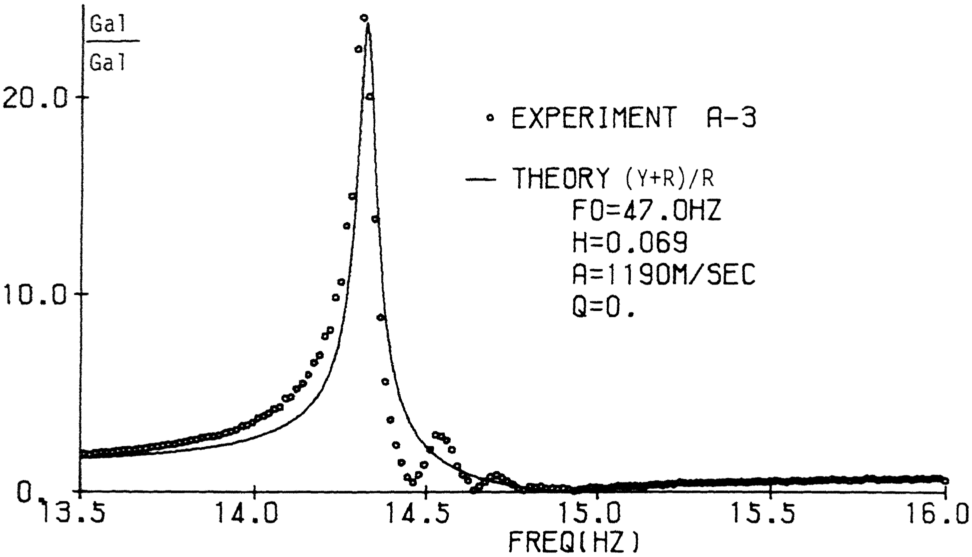


Fig.9 Pipe acceleration response A-3/A-2 by experiment and comparison with theory

a fairly low level. Fig.9 shows the pipe acceleration response at the main support position. The shape is about the same as pressure responses, but it comes to near zero at about 14.9Hz. This is explained as an anti-resonance caused by the balance of liquid pressure and shear force of supports. Fig.10 shows the response waves at resonance. The accelerations A-5,6 at pipe ends show larger values than that of the support position; that is, the longitudinal deformation of the pipe extended from the main supports appeared in the experiment. But, it's effect to hydraulic responses would be very small in this case.

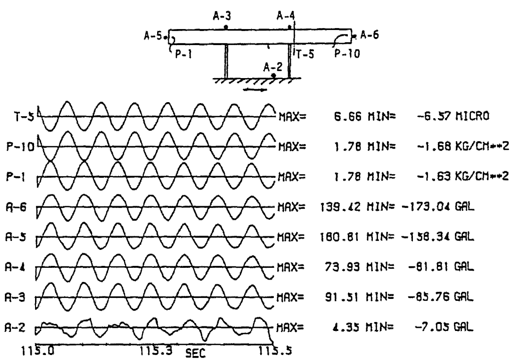


Fig.10 Response waves at resonance
T-5: pipe axial strain at main support position

Comparison with Analytical Model

The maximum response of the pipe will be much affected by support damping h and friction Q. Then, at first, the effects of h and Q to the maximum acceleration response were examined in 5-20Hz by use of Eq.(8). The result is shown in Fig.11.

Now, we use Q=0 considering that the pipe liquid friction will be very small for such a simple pipeline without column separation, then, we can obtain the apparent damping factor h=0.069 to correspond with the measured values.

The computed responses by h=0.069 and Q=0 are compared with the experiment in Fig.8,9. It can be seen that the simple analytical model is applicable as an approximation of a pipe-liquid coupled system.

Discussion on A Rigid Water Model

The response of a rigid water model is given by Eq.(8) by neglecting the fourth term of the denominator. When Q=0, this term is given by Eq.(12). It can be seen from Eqs.(8),(12) that the coupled response at near and lower than the first resonance will be

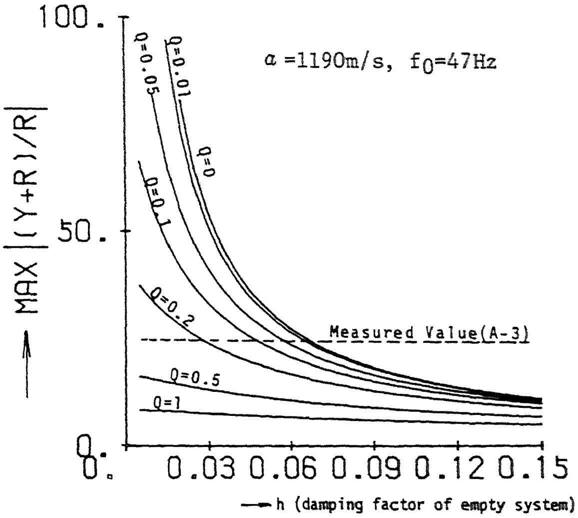


Fig.11 Maximum response value of analytical model for various value of h and Q (input frequency range: 5-20Hz)

$$H(a,\omega) = -m\omega^2 \left\{ \frac{\tan(\omega L/2a)}{(\omega L/2a)} - 1 \right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (12)$$

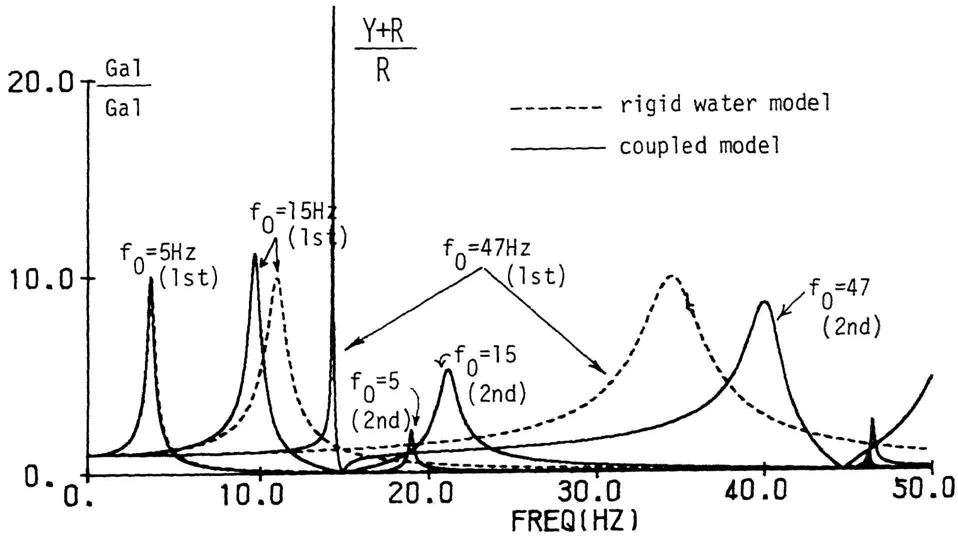


Fig.12 Comparison of the pipe acceleration response of a coupled model and a rigid water model for f_0=5,15,47Hz
(h=0.069, Q=0, a=1190m/s)

approximated by using $H(a,\omega)\approx 0$ if $\omega_0 \ll a\pi/L$. Fig.12 shows the comparison of the acceleration response (Y+R)/R of a coupled and a rigid water model for f_0=5,15,47Hz of empty natural frequency. This figure also shows the higher order resonances and the large effect of support stiffness in coupled response.

It is seen that the difference of the two model is remarkable and depends on the support stiffness. In the case of f_0=5Hz, that is very soft support, the response of the coupled model is almost equal to that of a rigid water model except for small responses of higher resonances. Thus, we can say as a rough estimate, that a rigid water model would be effective if the natural frequency of the empty system is smaller than the first resonance of the liquid column itself, that is, $f_0 \ll a/2L$. Otherwise, the difference between the two models is considerably large in both resonance frequency and response amplitude.

CONCLUSION

To investigate earthquake induced hydraulic effects to a piping system, a shaking table test was carried out and the very sharp resonance of a liquid-filled closed pipeline excited in axial direction was observed. This result was analyzed by use of a simple model of a straight pipe-liquid-support coupled system and the limitation of "rigid water model" was shown.

ACKNOWLEDGEMENTS

The author wishes to express his sincere gratitude to Dr. H. Shibata, Professor of the Institute of Industrial Science, Tokyo University, for his valuable advice throughout this work.

The author is grateful to Messrs. K. Narita, M. Yonezawa, M. Tsuji, T. Nakajima, H. Hayashi and other engineers of Nippon Kokan K.K. for their valuable suggestions in regard to the experiment. He also wishes to express his appreciation to Dr. F. M. Young, Professor of Lamar University, Texas, for his helpful discussions during this work. The author would like to thank Mr. H. Sebata of Hotaka Ltd. and Messrs. C. Minowa, S. Nomura, H. Iida of National Research Center for Disaster Prevention for their cooperation throughout the experiment.

REFERENCES

1. Youmg,F.M.,Hunter,S.E.,"Hydraulic Transients in Liquid-Filled Pipelines During Earthquakes",PVP-34(ASME),1979,pp143-151.
2. Nakagawa,Y.,"A Theoretical Study on The Water Pressure in Distributing Pipes During Earthquakes",Journal of Japan Water Works Association,No.416, 1969,pp26-35.
3. Ogawa,N.,"A Study on Dynamic Water Pressure in Underground Pipelines of Water Supply System During Earthquakes",PVP-43(ASME),1980,pp55-60.
4. Alipour,E.M.,Young,F.M.,"Approximations of Head and Flow Distributions in Liquid Filled Piping Networks Subject to Seismic Excitation Using A Steady Oscillatory Flow Model",Technical Report of Lamar University, 1981.